RIGID PILE RESPONSE TO ICE PLATE AND CURRENT LOADS

A Thesis

by

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May 1986

ABSTRACT

Rigid Pile Response to Ice Plate and Current Loads. (May 1986)

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The primary objective of this study was to develop a finite element model that accurately represents the interaction of ice, current, and soil with a single pile platform. A computer program was written to simulate the dynamic response of a rigid pile subject to ice plate and current loads. The governing system of differential equations were solved in the time domain using the Wilson Theta and Newmark Beta direct integration methods.

A new ice loading model was developed. The new model was compared to Matlock's original model and to the observed response of platforms installed in Cook Inlet. Results from the numerical examples indicates that the typical ratcheting behavior of the structure, which occurs during relatively slow ice velocities, can be minimized by detuning the platform. Current loading on the piles was also investigated, but was found to be negligible under most conditions. Modeling of the soil-structure interaction associated with the pile foundation did not change the general behavior of the piles for various ice velocities, however the maximum pile displacements at the ice surface were increased as much as 200%.

ACKNOWLEDGMENTS

This thesis research is a result of the excitement and interest in the field of Arctic offshore engineering that I experienced while taking a graduate course taught by Dr. John M. Niedzwecki. I am much indebted to him for his active support of my research work on ice-structure interactions and his continued interest in my work. I also would like to extend thanks to Dr. James K. Nelson and Dr. John M. Klinck for offering their constructive criticisms of the manuscript and their interest in the subject.

Finally, very special thanks are due to Cheryl, my wife, who with her love and patience supported me in writing this thesis.

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CHAPTER I

INTRODUCTION

HISTORICAL BACKGROUND

The Middle Ground Shoal field was the first commercial oil discovery in Cook Inlet, Alaska, and was discovered in the fall of 1963 by Shell Oil Co. With this discovery it became necessary to provide permanent structures for year-round drilling and production, however the conventional Gulf-Coast template type platform could not be used in Alaska due to the extreme ice forces. A new generation of platforms, tower-type structures with only large diameter legs protruding through the ice zone, were designed to resist the large forces encountered by the winter ice.

A year later, in the fall of 1964, Shell Oil Co. installed the first permanent drilling and production platform in Cook Inlet. In the following four years, an additional 14 tower-type platforms were installed in Cook Inlet. Of these 14 tower-type platforms, 11 were four-legged towers, two were three-legged towers, and one platform called the monopod is a single-legged tower.

The environmental conditions present in the Cook Inlet area, such as ice, tides, current, bitter cold and earthquakes, combine to produce one of the greatest challenges in the offshore oil engineering industry. The air temperatures in this area range from -40°F to 80°F,

The citations on the following pages follow the style of the Journal of Waterway, Port, Coastal and Ocean Engineering.

with an annual average of approximately 35°F. The water temperatures on the other hand range from a high of 55°F in the summer to a low of 29°F in the winter. During the winter months the upper Cook Inlet area is covered with ice that may have a maximum thickness of approximately 42 inches. The tides are among the highest in the world due to the configuration of the Inlet and its northern latitude, resulting in a maximum tidal variation of 30 feet. These high tides produce an extremely fast water current in the Inlet that ranges from 10 to 12 ft/sec. This water current is the driving force that moves the ice up and down the Inlet with approximately the same velocity as the current, exerting large crushing forces on all objects in its path. Besides all of the following environmental conditions, the entire Alaskan region is also in an active earthquake zone.

After the installation of the huge tower-type drilling platforms in Cook Inlet, an oscillating ice plate failure had been observed and recorded during times of very slow ice velocity, and the frequency of oscillation was about one cycle per second. The ice plate failure frequency is approximately the same as the resonant frequency of most large offshore platforms, and there exist a possibility of forced, resonant vibrations on the structure. This type of oscillation has been termed "racheting", and it can be a serious problem.

LITERATURE REVIEW

An Arctic reference list was compiled primarily focusing upon Arctic engineering papers appearing in the Offshore Technology Conference Proceedings, and this list is located in Appendix III. The objective of this review was to determine the trends in Arctic offshore engineering research over the last decade and a half. There are a number of other sources and publications in this field, however the proceedings from the Offshore Technology Conference should provide an adequate representation of the trends in Arctic engineering research.

The number of Arctic papers presented in the proceedings of the Offshore Technology Conference each year has steadily increased over the past fifteen years which can be seen clearly in Fig. 1. This growing interest in the Arctic began with the installation of the first offshore production platforms in Cook Inlet, and the problems associated with the design of these platforms. The first Arctic papers written were mainly focused on Cook Inlet structures and addressed problem areas such as ice-structure interaction, ice force prediction and measurement, and corrosion control. Shortly thereafter, additional articles were written dealing with such problems in the Arctic as oil spills, marine transportation, ice model testing, environmental data collection, sea ice scouring, earthquake analysis, and geotechnical considerations in Arctic designs.

Arctic offshore engineering research suddenly increased during the mid-seventies when the oil industry began exploration for oil in the Beaufort Sea. This lead to research in the design and construction of

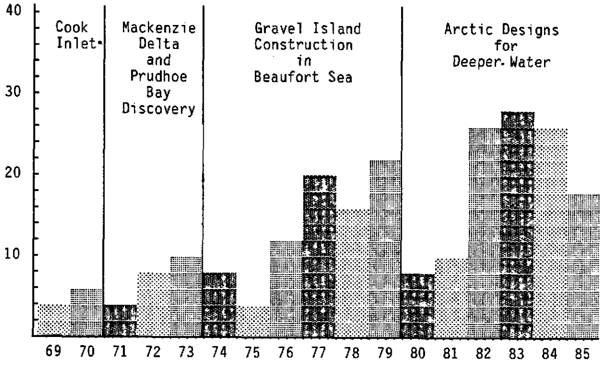

FIG. 1. — OTC Arctic Papers versus Years

artifical gravel islands which were used for exploratory drilling in relatively shallow waters. However, as exploration continued into the deeper waters of the Beaufort Sea, the construction of these gravel islands was no longer economically feasible. For this reason, engineers began to design large mobile Arctic caissons and floating drilling structures to drill in these deeper waters, and the articles found in the current literature reflect this trend towards deepwater Arctic structures.

The recent trend in Arctic offshore engineering research has been in the direction of deepwater Arctic structures, therefore additional information on the dynamic response of these structures to ice plate loading is needed for design purposes. This thesis investigation will attempt to provide some insight into the problem of ice-structure interaction which will be needed as oil exploration continues into deeper Arctic waters.

One of the first engineers to investigate sea ice properties was H.R. Peyton [6,7,8] during a three-year research study for Shell Oil Co. Peyton developed most of the necessary design background needed for the design of the Cook Inlet platforms. From this study, Peyton determined that the maximum ice thickness that could be expected during a 100-year period for Cook Inlet was about 42 inches. Field and laboratory test on ice samples conducted by Peyton indicated a maximum compressive strength of 550 psi and a design ice pressure of 300 psi.

Matlock [4,5] was the first to predict the response of Cook Inlet structures to an impinging ice sheet with a simple mechanical analog.

This simple single-degree-of-freedom model consisted of a spring-mass system which represented a cantilevered test pier, and the ice was modeled by a succession of elastic-brittle elements which impinge on the structure at a rate determined by the ice velocity. The dynamic response of the structure was calculated using a computer program to numerically solve the equation of motion.

An overview of the ice environment used for design calculations is presented in Table 1. The most critical issue is the mode of ice failure as it interacts with the structure. Recent structures have been designed with sloped sides to take advantage of the bending failure mode of the ice, since this results in an appreciable reduction in ice forces exerted on the structure. The properties of sea ice, the mechanisms which drive the ice plate, and the soil conditions in the Arctic and Sub-Arctic regions are still under investigation. In this thesis research, the dynamic response of a single pile will be analyzed in the time domain. The ice failure mode used in the model will be crushing since only vertical walled piles will be considered. Furthermore, the pile foundation will be addressed in the finite element model, and the current force beneath the ice cover will also be included in the analysis.

TABLE 1.— Previous Areas Investigated by Arctic Researchers

Author	Ice Failure Mode		Ice Properties	Ice Thickness in.	Ice Pressure psi	Driving Force	Response Domain	Soil
	Crushing	Bending						
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Peyton	Yes	Yes	Yes	36-42	300	Current 6-knots	Time	No
Matlock	Yes	No	No		300		Time	No
Blenkarn	Yes	No	No	25	125	Current 6-knots	Time	No
API-2N	Yes	Yes	Yes		550			Yes

THESIS RESEARCH OBJECTIVES

The primary objective of this thesis is to develop an engineering model, more elaborate than Matlock's simple single-degree-of-freedom system [4,5], to accurately predict the dynamic response of a rigid pile structure subject to ice plate and current loads. The structural stiffness of this cantilevered pile will be modeled by two-dimensional finite beam elements with two degrees of freedom at each node. The ice plate load is not modeled by finite elements, but instead will be modeled by using an oscillating saw-tooth type forcing function. The resulting system of differential equations for the finite element model can be integrated in the time domain using direct integration methods to calculate the response of the pile to an oscillatory or ratcheting type ice load.

There is no closed form solution for the system of differential equations. Therefore, a computer program will be written employing two direct integration methods to solve for the displacements, velocities, and accelerations of the structure. The two direct integration methods chosen were the Wilson Theta method and the Newmark Beta method. Both numerical techniques have been successfully used in many civil engineering applications, and their characteristics are reasonably well documented [2]. Since no exact solution exists, the results of the two methods will be compared against each other in view of the fact that numerical damping could occur in either method. In these numerical simulations one would like to use as few time steps as possible so that the ratio of the real time to the actual computational time can be maximized.

One of the major areas of interest that will be investigated is the effect of current and ice floes acting simultaneously on a rigid pile structure. This particular loading combination has not been studied in the current literature, but will be investigated in this thesis. Another area of concern is modeling the soil-structure interaction. In previous studies it has been assumed that the structure is fixed at the ocean floor, however this is not always a reasonable assumption for Arctic soil conditions. In this study the foundation will also be modeled by adding linear soil springs to the finite element stiffness matrix. The soil stiffness will be varied linearly from 30 lb/in^3 at the soil surface to 200 lb/in^3 at the bottom of the pile, and this range of soil stiffness should bracket the anticipated Arctic soil conditions. The effects of a damped system versus an undamped system, which was used by most of the past ice-structure interaction models, will be investigated. Furthermore, the response of the pile will be analyzed using slow, intermediate, and fast ice velocities.

The results of the computer program runs for the various test cases will be compared and analyzed by plotting the displacements of the pile at the ice surface versus time. Finally, the results obtained from this proposed finite element model will be compared to those obtained using Matlock's original model [4,5].

CHAPTER II

FORMULATION OF THE MODEL

FINITE ELEMENT MODEL

The system of differential equations of motion for the lumped-mass stick model shown in Fig. 2 can be written as

$$M \ddot{u} + C \dot{u} + K u = F_i(t) + F_c \quad (1)$$

where M = the mass matrix, C = the system damping matrix, K = the structural stiffness matrix, u = the displacement, $\dot{u}$ = the velocity, $\ddot{u}$ = the acceleration, $F_i(t)$ = the ice force applied at the still water level, and F_c = the current force beneath the ice cover. This system of equations can be integrated in the time domain using either the Wilson Theta or Newmark Beta direct integration methods to predict the response of the structure.

The structural stiffness of the pile was modeled using two-dimensional finite beam elements which were rotated 90°. The axial displacements of these elements were neglected since the order of their magnitudes are extremely small in comparison to the other two degrees of freedom. For static analysis the displacements of the element can be calculated by

$$F = K X \quad (2)$$

in which F = the load vector, K = the structural stiffness matrix, and X = the displacement vector.

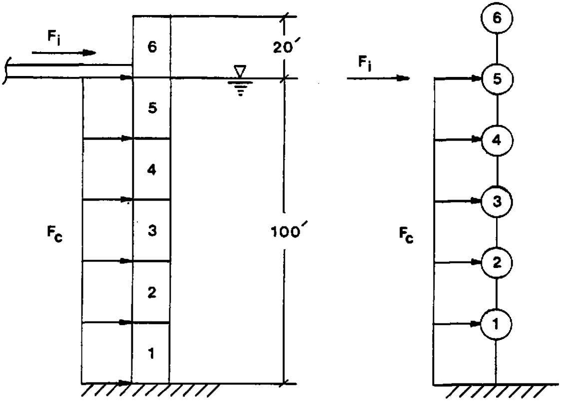

FIG. 2. — Finite Element Model of Fixed Pile Structure

Eq. 2 can be written in matrix form as

$$\begin{bmatrix} F_1 \\ M_1 \\ F_2 \\ M_2 \end{bmatrix} = \frac{2EI}{L^3} \left[\begin{array}{cc|cc} 6 & 3L & -6 & 3L \\ 3L & 2L^2 & -3L & L^2 \\ \hline -6 & -3L & 6 & -3L \\ 3L & L^2 & -3L & 2L^2 \end{array}\right] \begin{bmatrix} X_1 \\ \theta_1 \\ X_2 \\ \theta_2 \end{bmatrix} \quad \ldots\ldots (3)$$

for a finite beam element, where F = the horizontal force, M = the moment, X = the horizontal displacement, θ = the rotational displacement, L = the length of the element, E = the modulus of elasticity, and I = the moment of inertia.

The structural stiffness matrix in Eq. 3 can be written in shortened form as

$$K^{(1)} = \left[\begin{array}{c|c} K_{11}^{(1)} & K_{12}^{(1)} \\ \hline K_{21}^{(1)} & K_{22}^{(1)} \end{array}\right] \quad \ldots\ldots\ldots\ldots\ldots\ldots (4)$$

The structural stiffness matrix for the fixed pile shown in Fig. 2 which is divided into six elements can then be obtained by overlaying the common freedoms of the elements.

$$K = \begin{bmatrix} K_{11}^{(1)} & K_{12}^{(1)} & 0 & 0 & 0 & 0 & 0 \\ K_{21}^{(1)} & K_{22}^{(1)} + K_{22}^{(2)} & K_{23}^{(2)} & 0 & 0 & 0 & 0 \\ 0 & K_{32}^{(2)} & K_{33}^{(2)} + K_{33}^{(3)} & K_{34}^{(3)} & 0 & 0 & 0 \\ 0 & 0 & K_{43}^{(3)} & K_{44}^{(3)} + K_{44}^{(4)} & K_{45}^{(4)} & 0 & 0 \\ 0 & 0 & 0 & K_{54}^{(4)} & K_{55}^{(4)} + K_{55}^{(5)} & K_{56}^{(5)} & 0 \\ 0 & 0 & 0 & 0 & K_{65}^{(5)} & K_{66}^{(5)} + K_{66}^{(6)} & K_{67}^{(6)} \\ 0 & 0 & 0 & 0 & 0 & K_{76}^{(6)} & K_{77}^{(6)} \end{bmatrix} \quad (5)$$

This then is the assembled stiffness matrix for the entire structure.

In previous studies, Arctic offshore structures have been modeled by assuming that the structure is fixed at the ocean floor. However, this is not always a reasonable assumption especially for Arctic soil conditions. In this study, the foundation was modeled with linear soil springs which represent the soil-structure interaction of the pile. These soil springs are located at the nodal points of the stick model shown in Fig. 3 from the soil surface to the bottom of the pile, and the value determined for the stiffness of each spring is added to the diagonal terms of the finite element stiffness matrix, Eq. 5.

The soil stiffness, k_s, was varied linearly from 30 lb/in^3 at the soil surface to 200 lb/in^3 at the bottom of the pile as shown in Fig. 3. This range of soil stiffness should bracket the anticipated Arctic soil conditions. Assuming this range of values for k_s, the stiffness

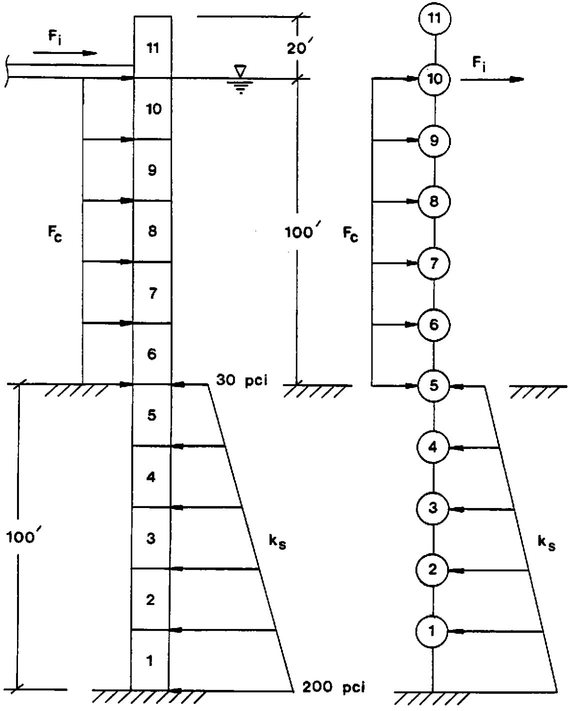

FIG. 3. — Finite Element Model of Pile and Foundation

of the soil springs at each of the nodal points can be calculated as

$$K_s = k_s D L \quad \text{. . . . . (6)}$$

where K_s = the spring stiffness, k_s = the soil stiffness at the node in question, D = the outer pile diameter, and L = the incremental length of the element.

The structural mass of the finite elements can be lumped at their nodal points as illustrated in Fig. 2 forming a lumped-mass stick model. For an element of uniform mass the simplest way to distribute the structural mass is to divide it equally between the ends of the element. Therefore, the mass at node 1 in Fig. 2 would be given by

$$M_1 = m_1 L_1/2 + m_2 L_2/2 \quad \text{. . . . . (7)}$$

where M_1 = the lumped mass at node 1, m_1 = the mass per unit length of element 1, m_2 = the mass per unit length of element 2, L_1 = the length of element 1, and L_2 = the length of element 2.

After the lumped mass at each nodal point is calculated, the mass matrix for the entire structure can be assembled as shown below.

$$M = \begin{bmatrix} M_1 & 0 & 0 & 0 & 0 & 0 & 0 \\ & 0 & 0 & 0 & 0 & 0 & 0 \\ & & M_2 & 0 & 0 & 0 & 0 \\ & & & 0 & 0 & 0 & 0 \\ & \text{SYMMETRIC} & & & \ddots & 0 & 0 \\ & & & & & M_N & 0 \\ & & & & & & 0 \end{bmatrix} \quad \text{. . . . . (8)}$$

SYSTEM DAMPING

The system damping for offshore structures is normally taken as a percentage of the critical damping which is given by

$$c_c = 2\,\omega_n\,M_n \quad \ldots\ldots \quad (9)$$

where c_c = the critical damping, ω_n = the free vibration frequencies of the structure in (rad/sec), and M_n = the lumped mass at node n. In previous dynamic analysis of offshore structures, the most frequently assumed percentage of the critical damping has been 5%. For lightly damped systems this is a reasonably good approximation, and therefore, will be used in the dynamic analysis of the rigid pile structure.

The undamped frequencies can be calculated as

$$\omega_n = (\lambda_n)^{\frac{1}{2}} \quad \ldots\ldots \quad (10)$$

where ω_n = the free vibration frequencies of the structure and λ_n = the eigenvalues. The undamped eigenvalues are determined from the solution of the following equation

$$K\,\Phi = \lambda\,M\,\Phi \quad \ldots\ldots \quad (11)$$

where K and M are, respectively, the structural stiffness matrix and mass matrix of the finite element model. The eigenvalues λ_n and eigenvectors Φ_n are the free vibration frequencies squared, ω_n^2, and corresponding mode shape vectors, respectively. Solution procedures for the generalized eigenproblem can be found in chapter ten of reference [2].

ICE PLATE LOADING

As an ice floe impinges on a pile type structure, the ice plate is fractured by crushing against the structure resulting in a localized failure zone being cut through the ice plate with debris piled along the sides. Matlock [4,5] represented the ice as an ideal elastic-brittle material in his model. Making this assumption, the ice force, F_1, acting on the structure will vary linearly and elastically with deformation of the ice to a maximum value. Once this maximum ice force is encountered fracturing of the ice occurs instantaneously, and the ice force returns back to zero. This saw-tooth type behavior of the ice force is shown in Figs. 4 and 5.

The maximum ice force, F_{max}, exerted by ice crushing against a pile can be expressed as

$$F_{max} = p\,D\,h \qquad (12)$$

where F_{max} = the maximum ice force, p = the ice pressure, D = the outer diameter of the pile at the region of ice contact, and h = the ice thickness. The ice pressure, p, on the pile can be calculated as

$$p = I\,f_c\,C_x \qquad (13)$$

where p = the ice pressure, I = the indentation factor, f_c = the contact factor, and C_x = the unconfined compressive strength of the ice. Peyton's analysis of ice forces on Cook Inlet structures suggests a maximum value of 0.55 for the product of (I x f_c) and a maximum value of 550 psi for C_x [6,7,8]. A comparison of the values of C_x obtained from the API-2N Bulletin versus Peyton's results are shown in Table 2 for the two piles used in the analysis.

TABLE 2.— Unconfined Compressive Strength of Sea Ice

			API-2N BULLETIN			PEYTON
			FIG. 3.2	FIG. 3.3	FIG. 3.4	
Pile	V_i ft/sec	$\dot{\epsilon}$ $(\mathrm{sec})^{-1}$	C_x lb/in^2	C_x lb/in^2	C_x lb/in^2	C_x lb/in^2
(1)	(2)	(3)	(4)	(5)	(6)	(7)
1	1	.0357	850	700	1000	550
	5	.1786	850	700	1000	550
	10	.3571	850	700	1000	550
2	1	.0178	850	700	1000	550
	5	.0893	850	700	1000	550
	10	.1786	850	700	1000	550

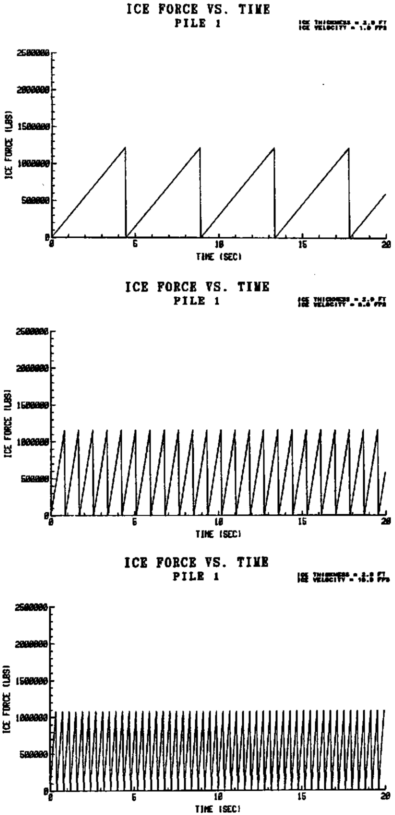

FIG. 4.— Ice Force on 14-ft-Diameter Pile

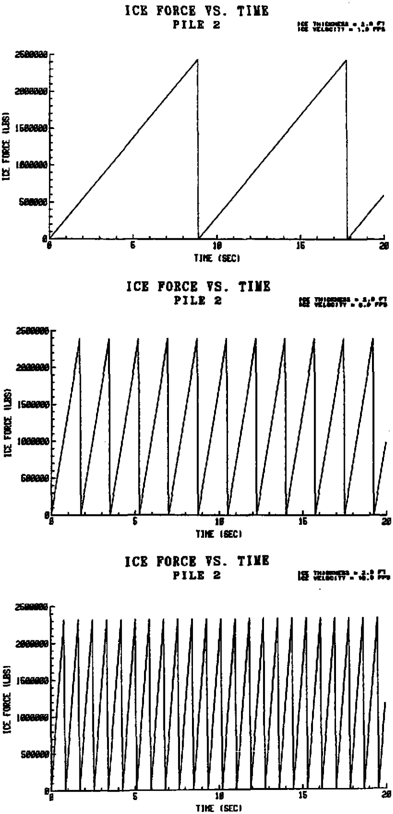

FIG. 5.— Ice Force on 28-ft-Diameter Pile

The ice plate loading was modeled by using a repeating saw-tooth type step function, shown in Figs. 4 and 5, in the differential equation of motion, Eq. 1. This step function for the ice force can be calculated as

$$F_i(t) = \frac{F_{max}}{T_i} (t - mT_i) \quad . . . . (14)$$

where $F_i(t)$ = the ice force as a function of time, F_{max} = the maximum ice force, T_i = the period of the step function, t = the time, and m = 0, 1, 2, ..., n. The ice force is varied linearly from zero to the maximum value over a period of time which is referred to as the rise time for the saw-tooth step function. This period for the step function can be calculated in terms of the strain rate of the ice as

$$T_i = (2\pi \dot{\epsilon})^{-1} \quad . . . . (15)$$

where T_i = the ice fracture period and $\dot{\epsilon}$ = the strain rate of the ice. Blenkarn [3] determined this rise time period during his study of ice forces on Cook Inlet structures, but he did not calculate the rise time period as a function of the strain rate. The strain rate of the ice can be calculated as

$$\dot{\epsilon} = V_i / 2D \quad . . . . (16)$$

where $\dot{\epsilon}$ = the strain rate of the ice, V_i = the ice velocity, and D = the outer diameter of the pile at the region of ice contact.

CURRENT LOADING

The past studies on ice-structure interactions found in the literature have neglected the water current beneath the ice cover in predicting the response of offshore structures to ice plate loading. In areas such as Cook Inlet, the velocity of the current can be extremely fast producing large drag forces on offshore structures and therefore should be investigated in the dynamic analysis of these structures. This study has included the effects of current and ice floes acting simultaneously on a rigid pile structure.

The high tidal range occurring in Cook Inlet produces an extremely fast water current in the Inlet with a maximum velocity of approximately 10 to 12 ft/sec. This water current is the driving force that moves the ice up and down the Inlet with approximately the same speed as the water. Therefore, in the model shown in Fig. 2 the velocity of the current was assumed to be equal to the ice velocity. Furthermore, the current velocity was also assumed to be constant along the length of the pile from the water surface to the sea floor. This approach will yield a conservative response estimate since the actual current may decrease with depth.

The drag force exerted on a pile as a result of the water current can be calculated as

$$F_c = \tfrac{1}{2} \rho C_d V_c^2 A \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (17)$$

where F_c = the current drag force, ρ = the water density, C_d = the drag coefficient, V_c = the incident water velocity, and A = the area of the pile projected normal to the flow. The current force applied at each of the nodal points in the finite element model shown in Fig. 2 can then be obtained by replacing the normal area of the pile, A, in Eq. 17 by the product of the diameter of the pile, D, times the incremental length of the elements, L.

CHAPTER III

NUMERICAL EXAMPLES

DATA FOR ANALYSIS

Using the finite element model formulated in the previous chapter and the computer program developed, the response of two steel piles were analyzed for a realistic range of ice loading cases, current loads, and soil conditions. Pile diameters of 14 ft and 28 ft were selected to correspond with two existing offshore structures which were installed in approximately 100 ft of water in Cook Inlet. Shell Oil Co. installed a four-legged platform in 1964 with 14-ft-diameter legs. Two years later, Union Oil Co. installed a single-legged platform with a 28-ft-diameter leg. The structural stiffness of the 28-ft-diameter pile is approximately double that of the 14-ft-diameter pile as a result of adjusting the inner diameter of the piles in order to investigate the effects of the structural stiffness on the response of the piles. A wall thickness of 1.5 in. was selected for the 28-ft-diameter pile. Therefore, the inner diameter of the 14-ft-diameter pile was adjusted until the desired structural stiffness was achieved, which resulted in a wall thickness of 6 in.

The response of these two piles were analyzed first for ice plate loading only, neglecting any current loads on the structure. Then, the response was predicted for current and ice floes acting simultaneously on the piles. An ice plate thickness of 2 ft, which is an average ice thickness for Cook Inlet, was selected to simulate the actual ice plate loading on offshore structures installed in the Inlet. Based upon Peyton's research on sea ice in Cook Inlet, the maximum ice pressure exerted on the piles was assumed to be 300 psi. The velocity of the current and ice impinging upon the piles was assumed to be equal, and the piles were analyzed using slow, intermediate, and fast ice velocities. The three ice velocities used in the analysis of the two piles were 1, 5, and 10 ft/sec.

Two separate soil cases were included in the analysis of the piles. The first soil case used in the analysis assumes that the piles are fixed at the sea floor, which has been the assumption made by most of the previous studies on ice-structure interaction. The second soil case considered is shown in Fig. 3 and actually models the foundation by adding linear soil springs to the finite element stiffness matrix. The soil stiffness was varied from 30 lb/in^3 at the soil surface to 200 lb/in^3 at the bottom of the piles, and the embedded soil depth of each of the piles was assumed to be 100 ft.

DIRECT INTEGRATION METHODS

Two direct integration methods were used in the computer program to calculate the response of the piles by integrating the system of differential equations developed in the time domain. The Wilson Theta method and the Newmark Beta method were the two methods chosen for the analysis, because both numerical techniques have been successfully used in many civil engineering applications, and their characteristics are reasonably well documented [2]. Since there is no closed form solution for the system of differential equations, the results of the two methods were compared against each other for various test cases.

A time step size of .05 sec was assumed for both numerical techniques, and the response of the structure over a time frame of 20 sec was then calculated by using 400 time steps in the analysis. There was no noticeable difference between the results of the two methods for predicting the response of the structure. Therefore, the solutions obtained from the analysis should be reasonably accurate, and there is no reason to suspect that any numerical damping exist over this time range. Numerical damping is known to occur when the Wilson Theta method is used for the calculation of high frequency response. Therefore, the Newmark Beta method was used as a bench mark since this method is known to be more accurate [2]. Since the plots of the pile response predicted by both numerical methods were identical, those predicted by the Wilson Theta method were omitted.

RESPONSE OF RIGID PILE PLATFORMS

The predicted response of the two test piles calculated by the computer program are presented in the figures in this section. The typical response of the 14-ft-diameter and 28-ft-diameter piles that are assumed to be fixed at the sea floor are shown in Figs. 6 and 7 for three different ice approach velocities. Each figure consists of three plots of the pile displacements at the ice surface versus time for slow, intermediate, and fast ice velocities.

The predominant response of the structure is a saw-tooth type deflection which occurs during relatively slow ice velocities. This behavior known as ratcheting can be observed quite clearly at an ice velocity of 1.0 ft/sec which is plotted at the top of Fig. 6. At this velocity the ice plate deflects Pile 1 linearly to a maximum value of .19 ft at which time enough energy has been stored in the structure to fracture the ice, and the pile crushes rapidly through the ice plate returning almost to its initial position. Once this point is reached, all the stored energy in the structure has been expended by crushing through the ice plate. The structure no longer has the energy required to crush the ice, and the moving ice plate begins deflecting the pile in the positive direction again. This ratcheting behavior of the pile continues to repeat itself indefinitely with a constant period for slow ice velocities.

For fast ice velocities, the typical response of the structure is illustrated by the plot at the bottom of Fig. 6. At an ice velocity of 10.0 ft/sec, the pile oscillates with a constant amplitude of .015 ft

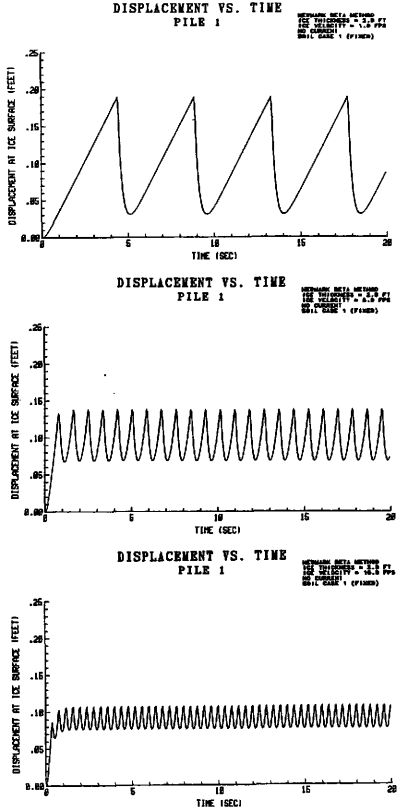

FIG. 6. — Response of 14-ft-Diameter Pile — Fixed

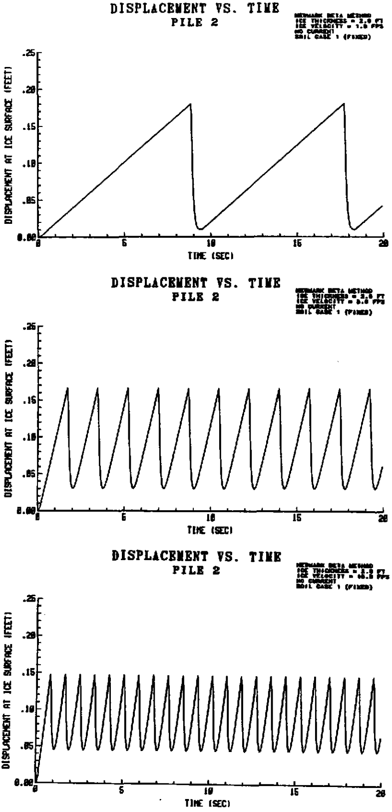

FIG. 7.— Response of 28-ft-Diameter Pile – Fixed

about a mean displacement of .09 ft which is approximately half of the maximum deflection of the pile at an ice velocity of 1.0 ft/sec. This general behavior, where the mean displacement at fast ice velocities is half of the maximum displacement at slow ice velocities, was observed in the results of the test cases and was also predicted by Matlock's model. One explanation for this response is that since the ice fracture frequency at fast ice velocities is much larger than the natural frequency of the structure, the pile actually feels a continuous average ice force instead of the extremely large ice forces encountered at slow ice velocities.

The effects of the structural stiffness on the response of the piles can be seen by comparing the plots at the top of Figs. 6 and 7. The stiffer the pile the more the structure tries to return to its at rest position after fracturing the ice which is clearly seen by comparing the response of Pile 2 in Fig. 7 to that of Pile 1 in Fig. 6. The structural stiffness of Pile 2 is approximately double that of Pile 1, therefore one would expect that the maximum deflection of Pile 1 would be larger than that of Pile 2 by a factor of two. However, the maximum deflection for both piles is equal because the ice force exerted on Pile 2 is exactly twice that exerted on Pile 1 as a result of the piles' outer diameters being different.

The general behavior of the piles for slow, intermediate, and fast ice velocities does not change by modeling the soil-structure interaction. However, a noticeable difference in the magnitudes of the maximum pile deflections was encountered as shown in Figs. 8 and 9.

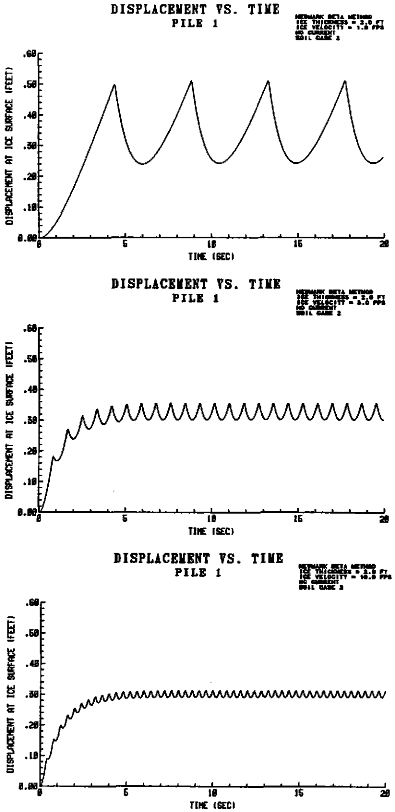

FIG. 8.— Response of 14-ft-Diameter Pile – Soil Modeled

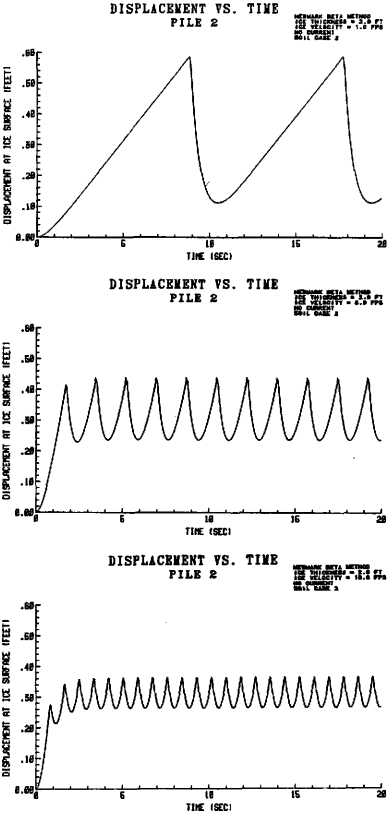

FIG. 9.— Response of 28-ft-Diameter Pile — Soil Modeled

The maximum deflections for the piles with the soil modeled were as much as 200% greater than those of the fixed piles. These larger displacements are a result of the total length of the pile being 100 ft longer when the foundation is modeled which decreases the stiffness of the structure. As a result of the stiffness decreasing, the pile is unable to return to its initial position after fracturing the ice. The response of Pile 1 shown at the top of Fig. 8 illustrates this behavior. The pile oscillates between a maximum deflection of .50 ft and a minimum deflection of .24 ft, instead of returning to its at rest position. The size of the ratchet depth was also noticed to increase by a considerable amount when the soil-structure interaction was investigated. Modeling the foundation is not required to predict the general behavior of the piles, however the soil-structure interaction should be investigated for design purposes in order to determine the maximum deflection of the structure.

In this study the effects of current and ice floes acting simultaneously on a rigid pile structure were also investigated. As shown in Figs. 10 and 11, the additional drag force from the current had no apparent effect on the response of the structure. The current had no effect on the pile response because the drag force has a magnitude in the range of 100 lb, whereas the ice force has a magnitude in the range of 1,000,000 lb. Furthermore, ratcheting occurs during relatively slow ice velocities, and assuming that the current velocity is approximately the same as the velocity of the ice plate, the current force would therefore be negligible during the ratcheting process.

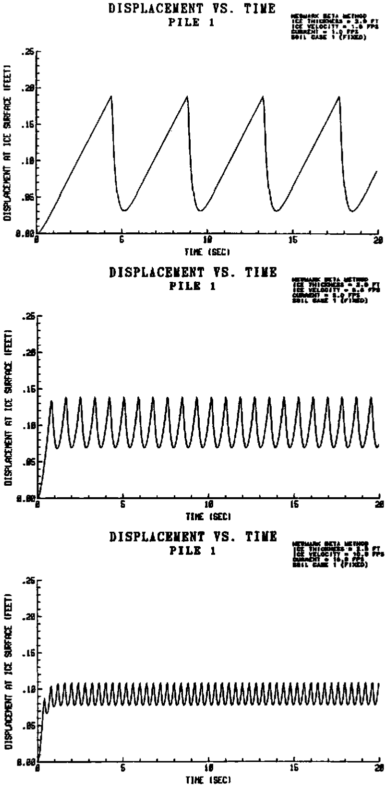

FIG. 10. — Response of Pile 1 to Ice and Current Loads

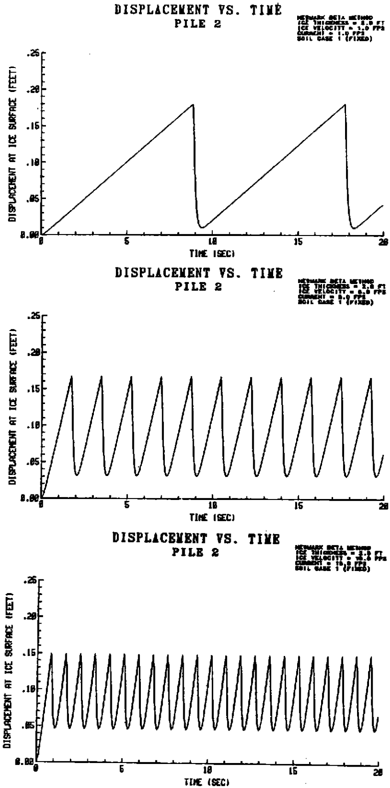

FIG. 11. — Response of Pile 2 to Ice and Current Loads

It is interesting to note that the results from the finite element model indicates that the typical ratcheting behavior of the structure can be minimized by detuning the platform. By adding a large deck mass to the top of the platform the natural period of the structure can be increased, thus essentially detuning the structure from the ice fracturing period. The dynamic response of the detuned platform is shown in Fig. 12, and the typical ratcheting behavior is almost non-existent.

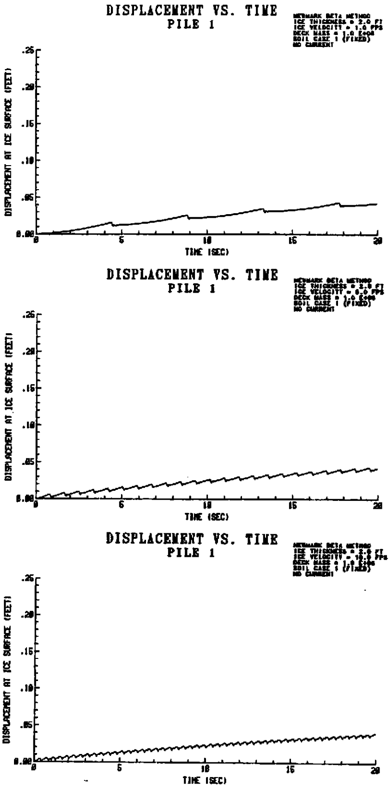

FIG. 12. — Response of Detuned Structure

CHAPTER IV

SUMMARY AND CONCLUSIONS

A finite element model was developed that accurately represents the interaction of ice, current, and soil with a single-pile platform. To simulate the dynamic response of this rigid pile platform to ice plate and current loads, a computer program was written that solves the governing system of differential equations in the time domain using the Wilson Theta and Newmark Beta direct integration methods. The general pile response predicted by the new ice loading model compares reasonably well with the results of Matlock's original model [4,5] and the observed behavior of offshore platforms installed in Cook Inlet. Current loading on the piles was also investigated, but was found to be negligible under most conditions. Modeling of the soil-structure interaction on the other hand was found to have a significant difference in the response of the structure. As a result of this study, two possible solutions to minimize the typical ratcheting behavior of offshore platforms subject to ice loading were obtained.

The general behavior of the piles for slow, intermediate, and fast ice velocities did not change by modeling the foundation, however the maximum pile displacements at the ice surface were as much as 200% greater than those of the fixed piles. Therefore, the soil-structure interaction should be investigated for design purposes in order to determine the maximum pile deflection at the ice surface. Due to the limited number of articles on Arctic soil properties reported in the literature, additional research in this area is recommended and required in order to accurately predict the response of offshore Arctic structures.

The results from the numerical examples indicates that the typical ratcheting behavior of the structure can be minimized by detuning the platform. This can be accomplished by adding a large deck mass to the top of the platform which essentially detunes the structure from the ice fracturing period. The ratcheting behavior can also be minimized by decreasing the structural stiffness of the pile, because the stiffer the pile the more the structure tries to return to its at rest position after fracturing the ice.

The ice plate loading used in the analysis was assumed to be a repeating saw-tooth type step function as shown in Figs. 4 and 5. Additional field and laboratory experiments are recommended to verify this assumed ice forcing function and to give a better understanding of ice-structure interactions. Since the developed finite element model is solved in the time domain, future Arctic researchers could use actual real time data of ice force measurements from field or laboratory experiments in the forcing function of the model instead of the repeating saw-tooth type step function. The accuracy of the finite element model could then be determined by making a comparison between the predicted response and the actual measured response.

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APPENDIX II.— NOTATION

The following symbols are used in this paper:

A = area of the pile projected normal to the current flow;

C = system damping matrix;

c_c = critical damping;

C_d = drag coefficient;

C_x = unconfined compressive strength of sea ice;

D = outer diameter of the pile at the region of ice contact;

E = modulus of elasticity;

F = load vector;

F_c = current force beneath the ice cover;

f_c = ice contact factor;

$F_i(t)$ = ice force applied at SWL;

F_{max} = maximum ice force;

h = ice thickness;

I = moment of inertia and ice indentation factor;

K = structural stiffness matrix;

K_s = soil spring stiffness;

k_s = soil stiffness at the node in question;

L = length of the element;

M = mass matrix and moment;

m = mass per unit length of the element;

M_n = lumped mass at node n;

p = ice pressure;

T_i = ice fracture period;

t = time;

u = displacement;

$\dot{u}$ = velocity;

$\ddot{u}$ = acceleration;

V_c = incident water velocity;

V_i = ice velocity;

X = displacement vector;

$\dot{\epsilon}$ = strain rate of the ice;

θ = rotational displacement;

λ_n = eigenvalues;

ρ = water density;

Φ_n = eigenvectors; and

ω_n = free vibration frequencies of the structure.

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